# MEASURING THE UNMEASURABLE

## WHY MEASUREMENTS ALONE CANNOT QUANTIFY AEROSOL RADIATIVE FORCING OF CLIMATE CHANGE

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BROOKHAVEN NATIONAL LABORATORY

*Symposium on*

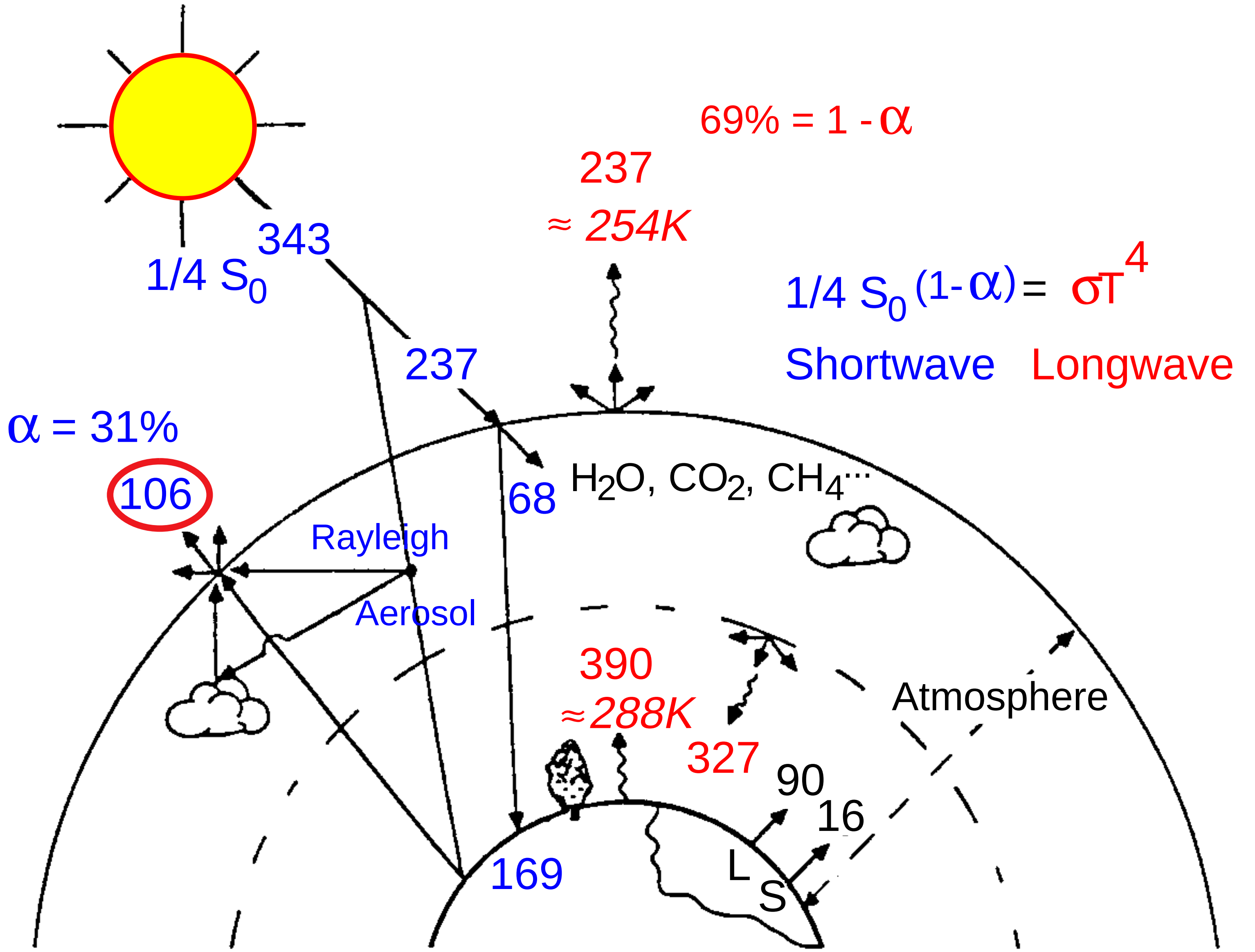
The Global Aerosol System:

Global and Regional Assessments

http://www.ecd.bnl.gov/steve/schwartz.html

# GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter




*Modified from Ramanathan, 1987*

# REQUIREMENTS FOR DETERMINING AEROSOL RADIATIVE FORCING OF CLIMATE CHANGE

***Perturbation*** of net irradiance at the top of the atmosphere (TOA) due to ***anthropogenic*** aerosols.

Accuracy better than ± 0.5 W m$^{-2}$ (*Schwartz, AGU, Fall, 2003; JAWMA, 2004*).

Based on determining climate sensitivity to ± 30%.

***Hypothesis***: Forcings of troposphere–surface system are additive and fungible in global-annual average.

***Requirement***: Anthropogenic aerosol radiative flux perturbation as a function of space (360° × 180°) and time (24 × 365).

***Challenges***: Aerosol forcing is highly variable in space and time.

Total upwelling shortwave irradiance is highly variable in space and time.

# APPROACHES TO DETERMINE AEROSOL **DIRECT** RADIATIVE FORCING

## 1. Satellite Irradiance Method

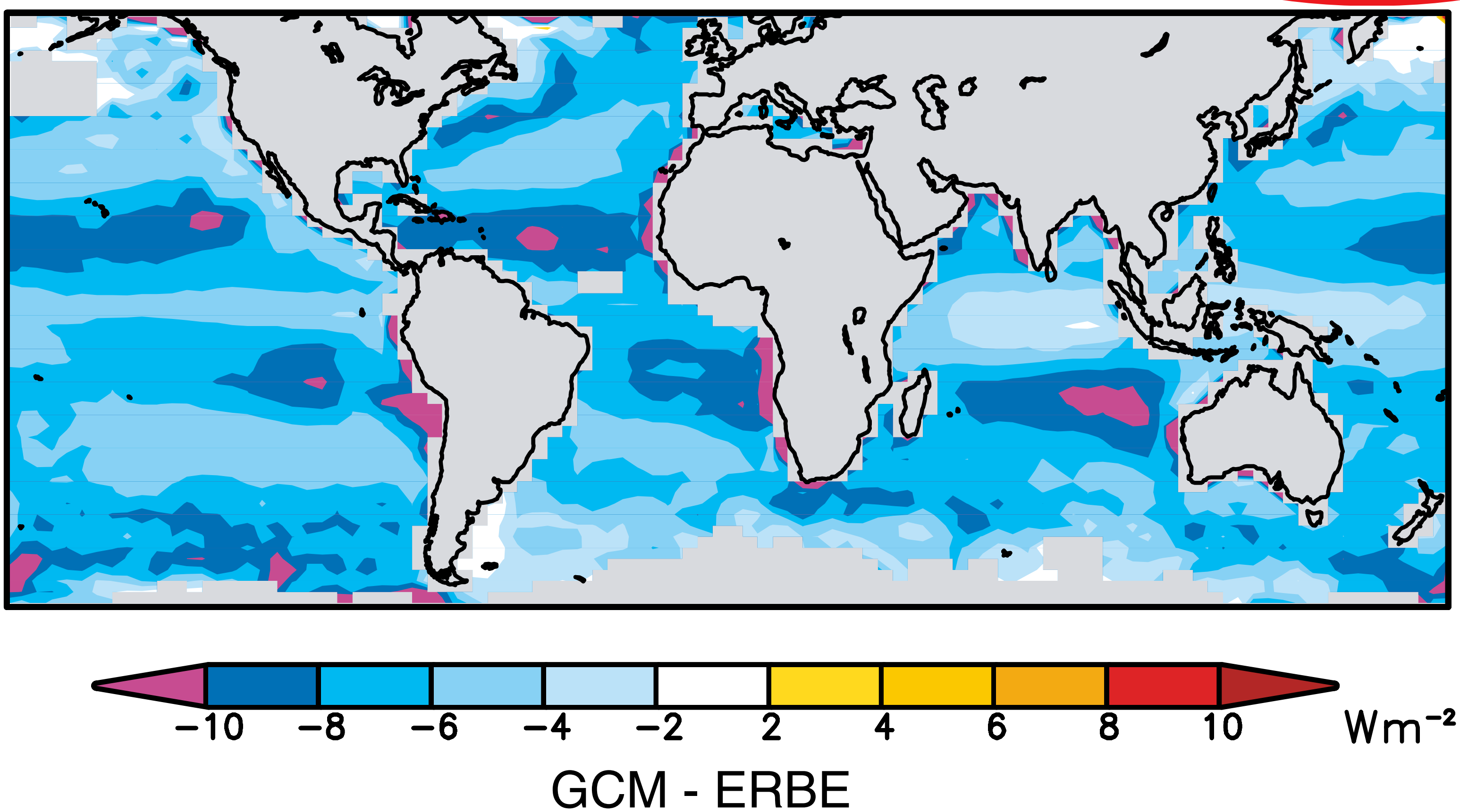
Satellite determination of upwelling irradiance.

Compare to modeled aerosol-free irradiance.

| STRENGTHS | LIMITATIONS/CONCERNS |
|---|---|
| Global coverage. | Requires model of total upwelling clear-sky irradiance including surface irradiance. |
| | Satellite calibration. |
| | Scene contamination by clouds (wide FOV). |
| | Bias toward low humidity (cloud free). |
| | Aerosol irradiance is small fraction of total. |
| | Sparse temporal coverage. |
| | No attribution to anthro. |

# AEROSOL FORCING FROM SATELLITE IRRADIANCE

Annual-average difference between measured irradiance and model without aerosol for cloud-free sky – Global average -6.74 W $m^{-2}$




*Haywood et al., Science, 1999*

*No attribution to substances.*

*Difference field incorporates all errors in modeled irradiance.*

# APPROACHES TO DETERMINE AEROSOL **DIRECT** RADIATIVE FORCING (*cont'd*)

## 2. Satellite AOT Method

Satellite determination of aerosol contribution to path radiance.

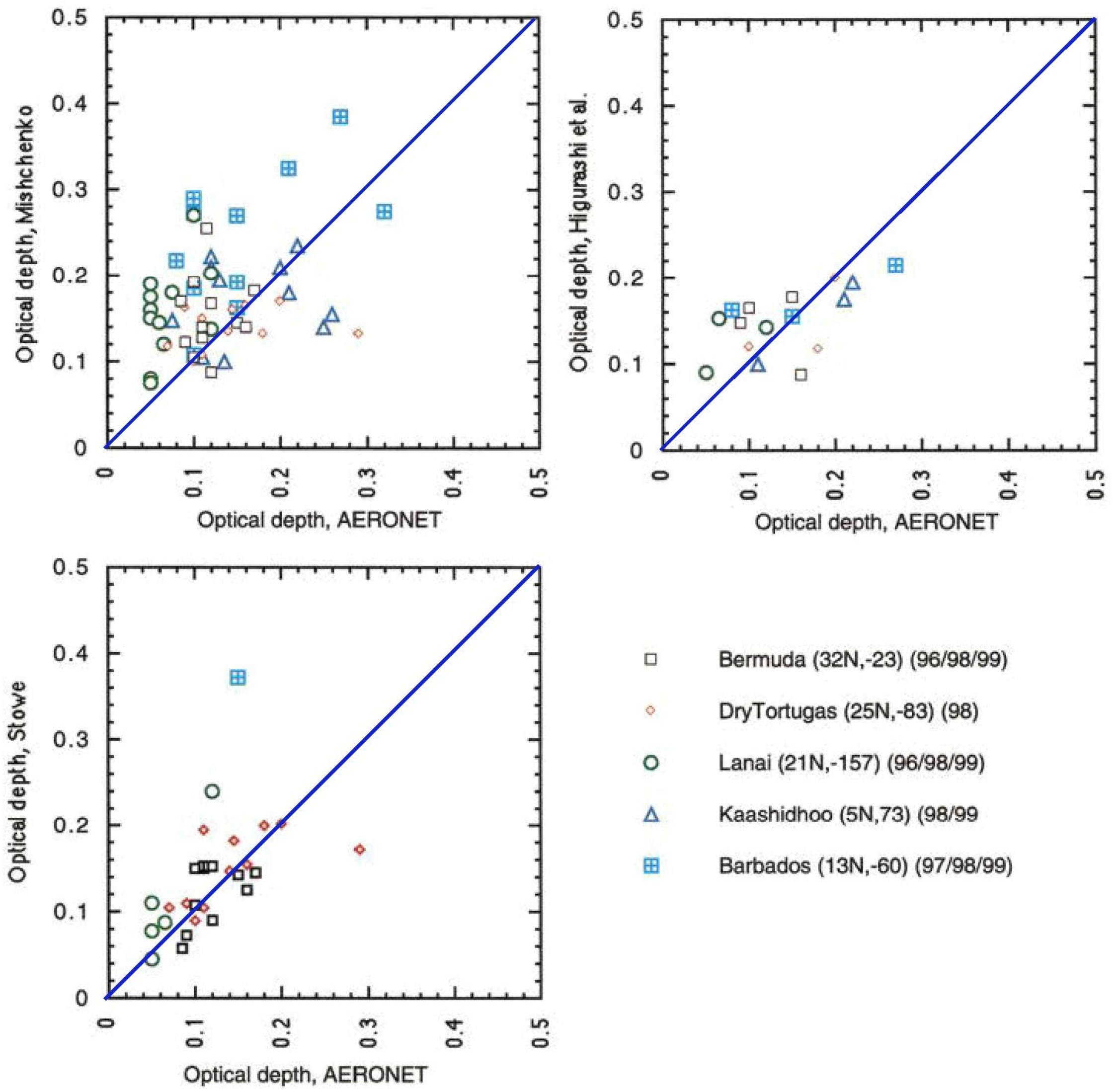
Model aerosol radiance to aerosol optical thickness (AOT).

Model TOA forcing from AOT.

| STRENGTHS | LIMITATIONS/CONCERNS |
|---|---|
| Global coverage. | Non-aerosol contribution to path radiance. |
| | Radiance-to-AOT conversion. |
| | Sensitivity to aerosol optical properties. |
| | Accuracy of satellite AOT. |
| | AOT-to-forcing conversion. |
| | Sensitivity to aerosol optical properties. |
| | Sparse temporal coverage. |
| | No attribution to anthro. |

# COMPARISON OF SATELLITE AND GROUND BASED MEASUREMENTS OF AEROSOL OPTICAL THICKNESS

## Monthly-mean AVHRR measurements over oceans (550 nm) vs. AERONET

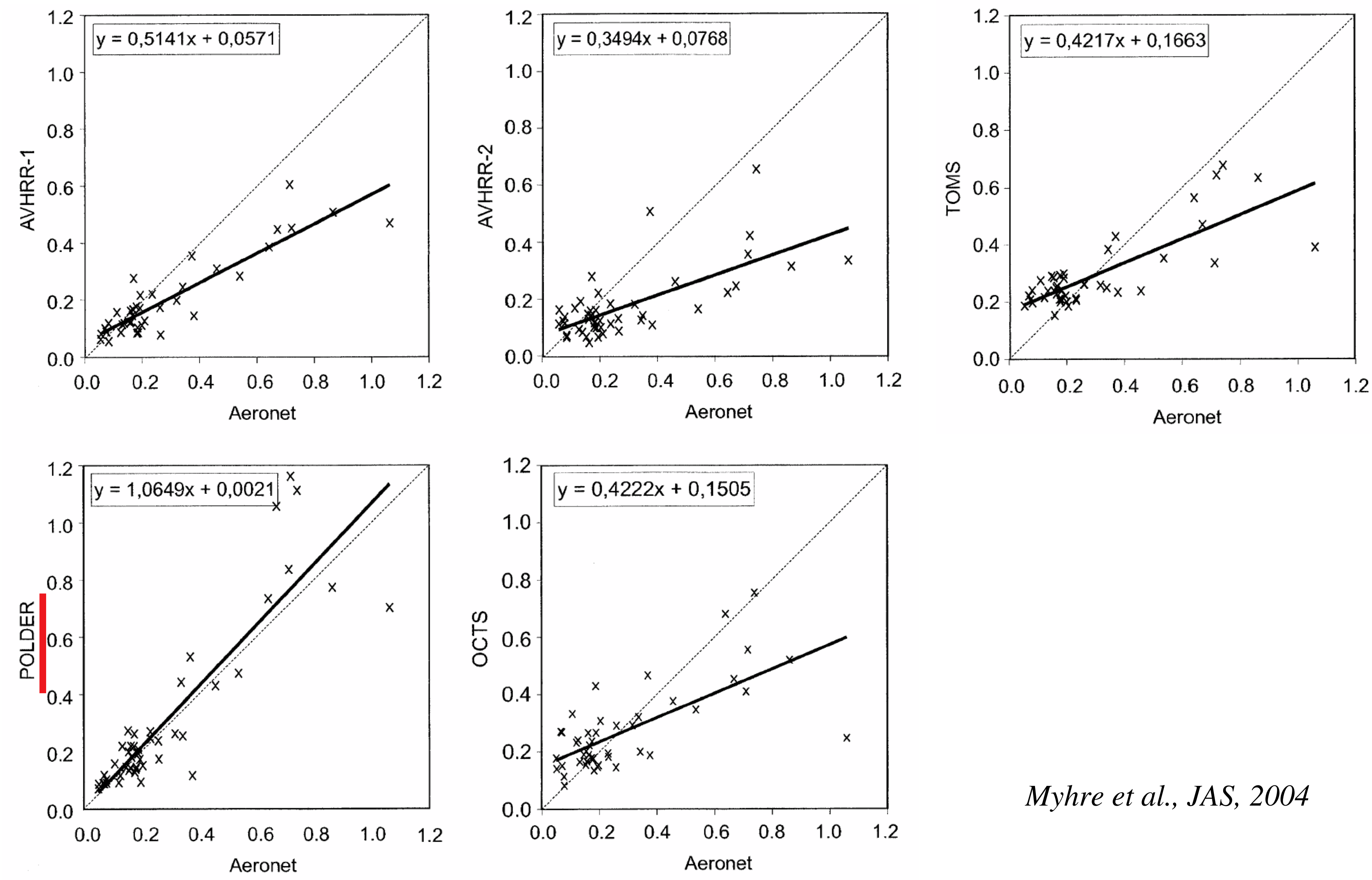



*Penner et al., JAS, 2002*

# COMPARISON OF SATELLITE AND GROUND BASED MEASUREMENTS OF AEROSOL OPTICAL THICKNESS

## Monthly-mean measurements over oceans

Satellite data at 550 nm, AERONET data mean of 440 (500) and 670 nm

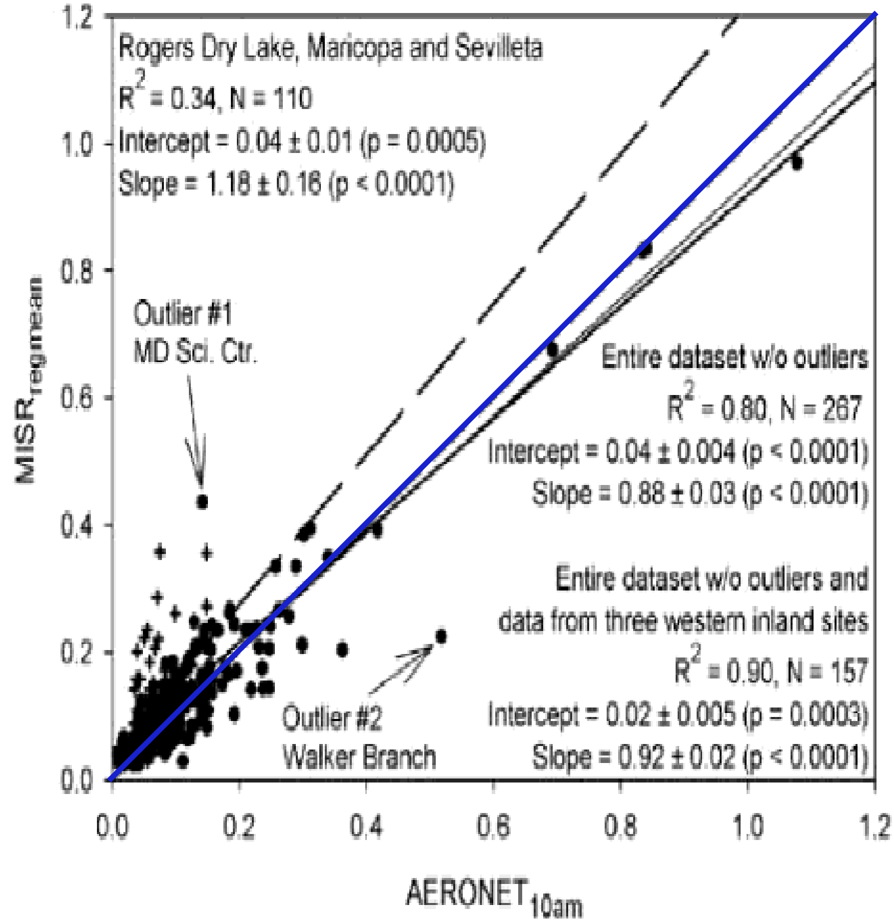



*Myhre et al., JAS, 2004*

# COMPARISON OF SATELLITE AND GROUND-BASED MEASUREMENTS OF AEROSOL OPTICAL THICKNESS

Individual measurements over ***land stations***

MISR data at 558 nm, AERONET data interpolated from 440 and 675 nm




*Liu et al, JGR, 2004*

Accuracy within ±0.02 ±0.10 AOT (excluding outliers and sites influenced by desert dust).

# APPROACHES TO DETERMINE AEROSOL **DIRECT** RADIATIVE FORCING (*cont'd*)

## 3. Ground-based AOT Method

Ground-based measurement of AOT.

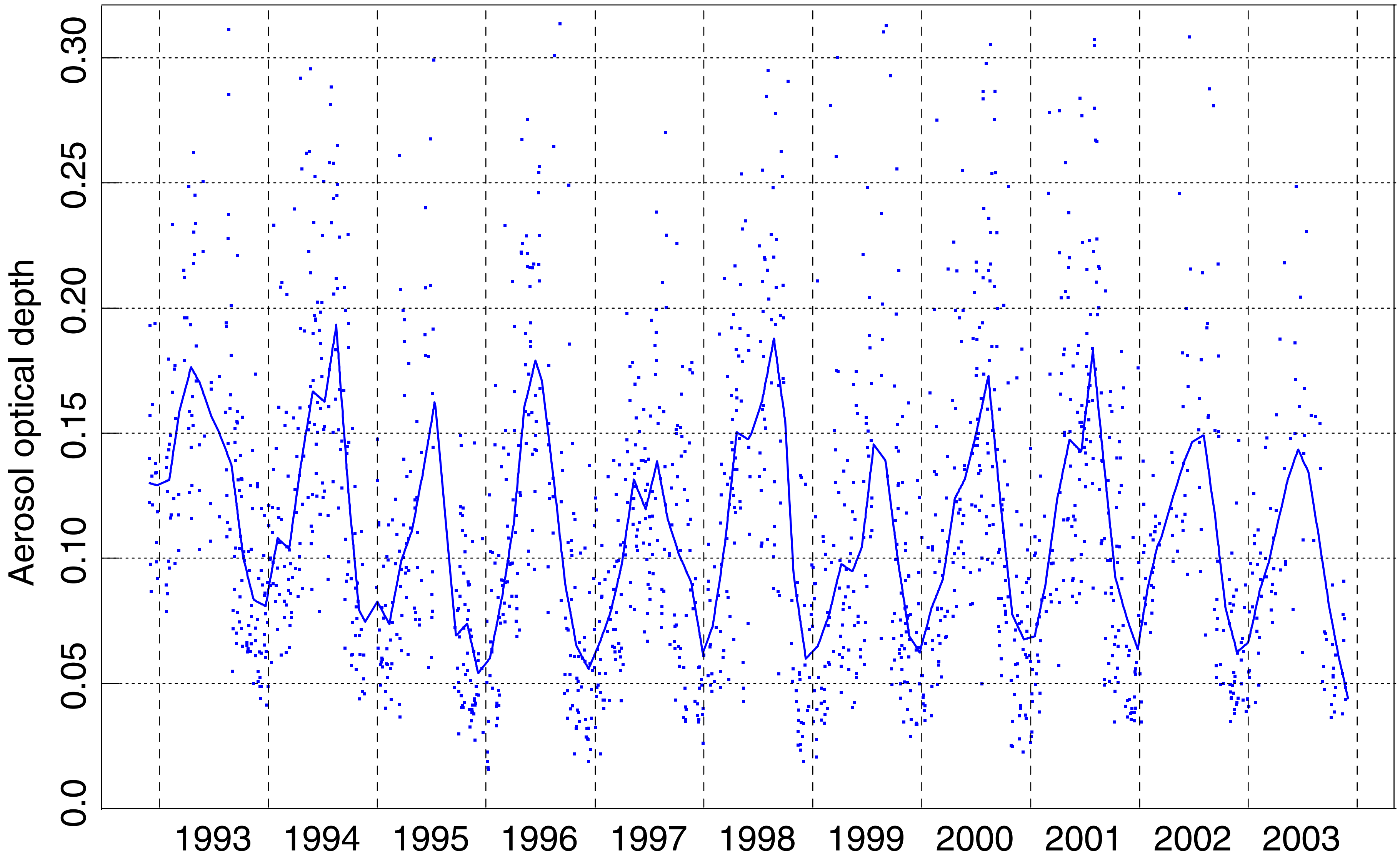
Model TOA forcing from AOT.

| STRENGTHS | LIMITATIONS/CONCERNS |
|---|---|
| Unequivocal AOT | AOT-to-forcing conversion. |
| Temporal coverage | Sensitivity to aerosol optical properties. |
| | Sparse spatial coverage. |
| | No attribution to anthro. |

# AEROSOL OPTICAL DEPTH

## Determined by sunphotometry

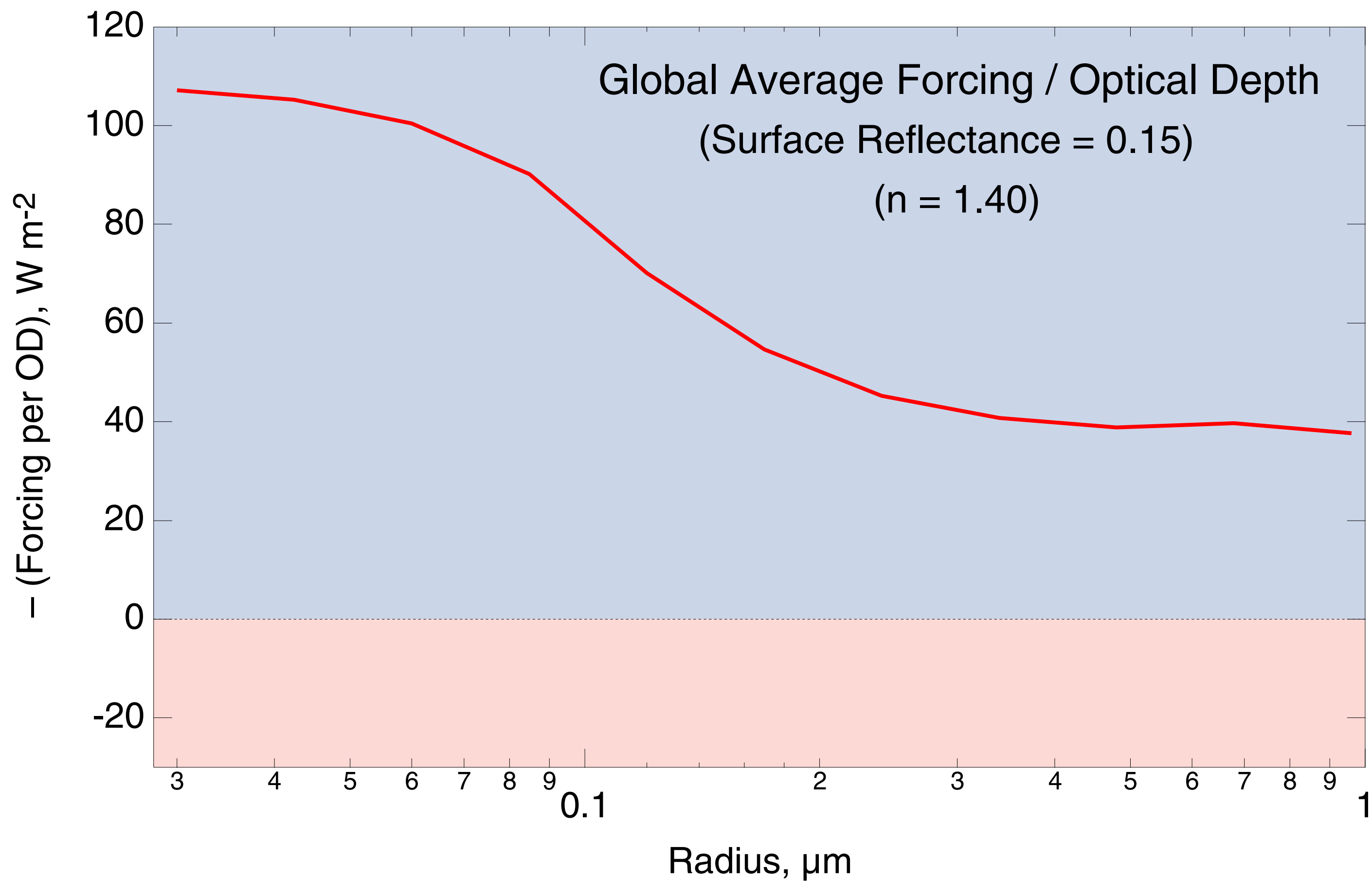
## North central Oklahoma - Daily average at 500 nm




*J. Michalsky et al., JGR, 2001*

# FORCING PER OPTICAL DEPTH

## Global average, cloud-free sky - Scattering aerosol

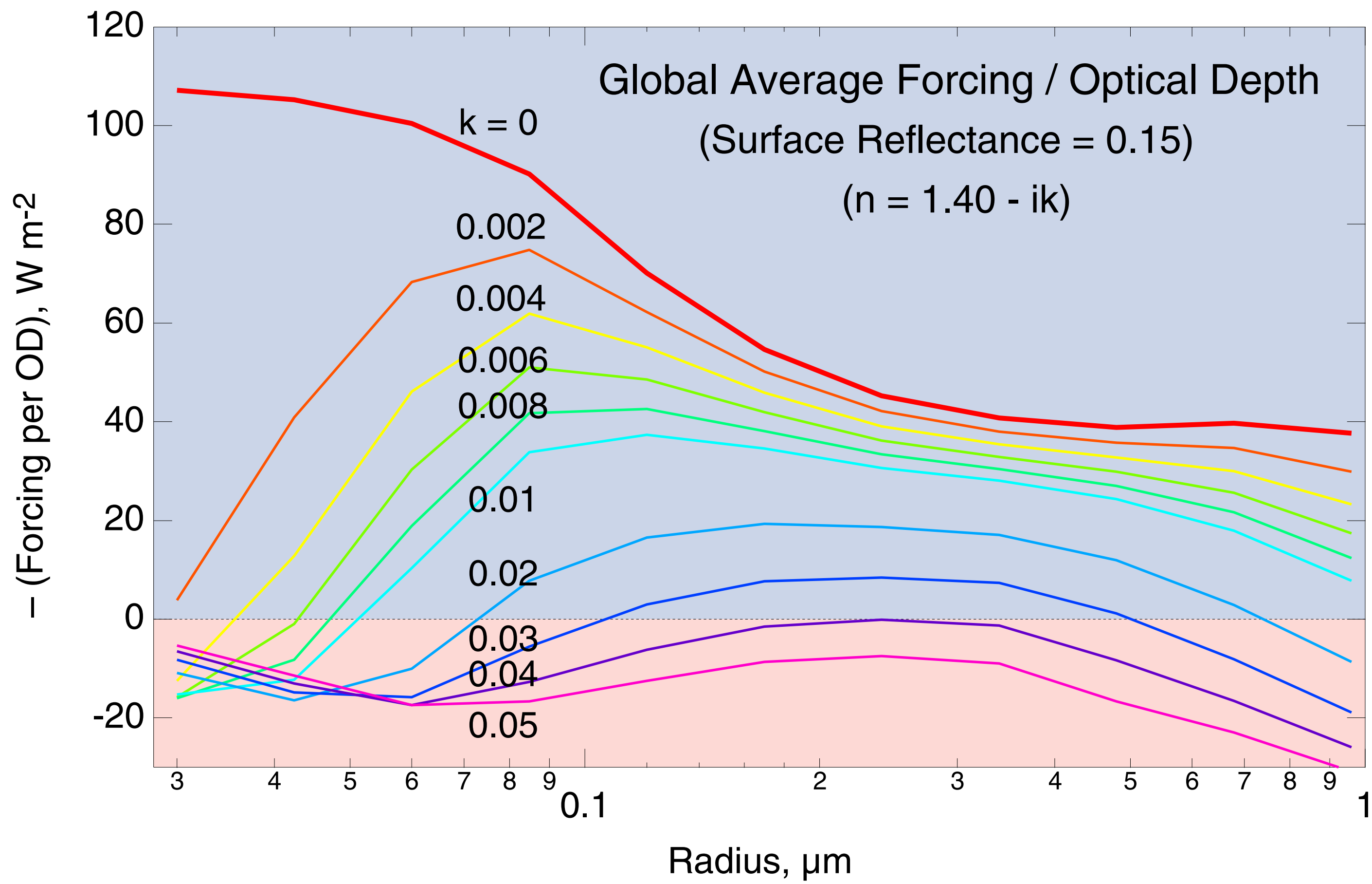



*Forcing per optical depth depends rather strongly on particle size.*

*Forcing accuracy 0.5 W $m^{-2}$ requires optical depth accuracy 0.005 - 0.01 (0.01 - 0.02 for 60% cloud cover).*

# FORCING PER OPTICAL DEPTH

## Global average, cloud-free sky - Absorbing aerosol




*Forcing per optical depth depends rather strongly on particle size – and also rather strongly on aerosol absorption.*

# APPROACHES TO DETERMINE AEROSOL **DIRECT** RADIATIVE FORCING (*cont'd*)

## 4. Surface Forcing Method

Ground-based measurement of aerosol surface forcing.

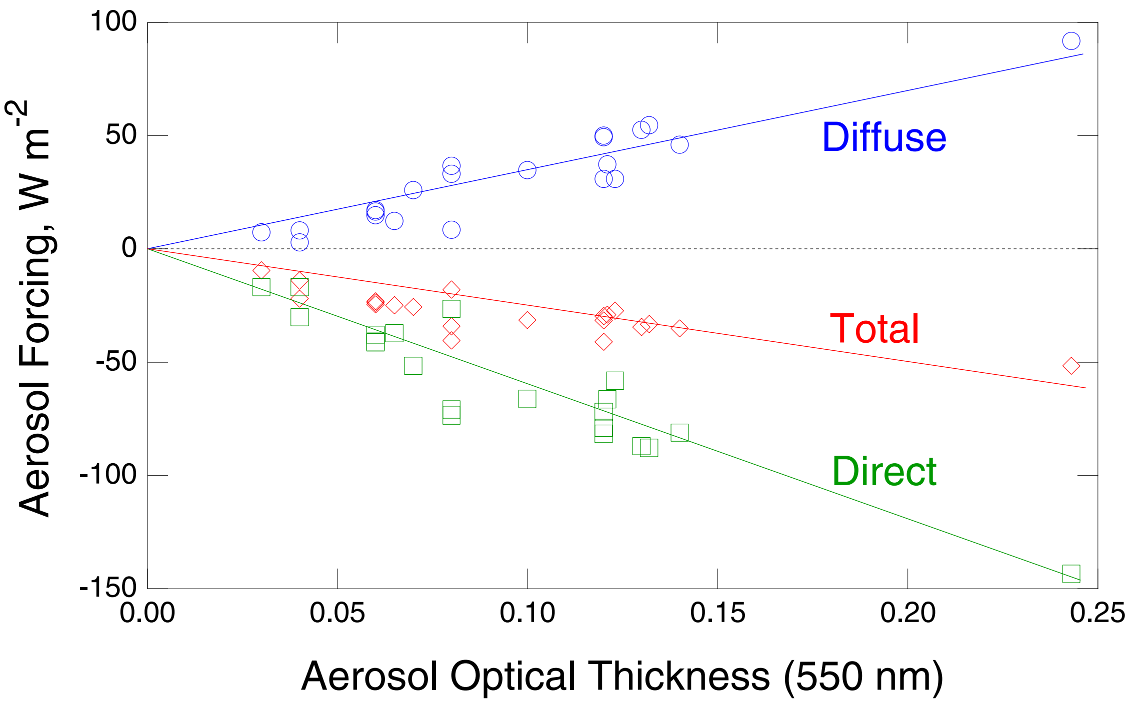
Model TOA forcing from AOT.

| STRENGTHS | LIMITATIONS/CONCERNS |
|---|---|
| Unequivocal surface forcing (Rayleigh background). | Surface-to-TOA forcing conversion. Sensitivity to aerosol optical properties.<br>Sparse spatial coverage.<br>Sparse temporal coverage (cloud free only). Bias to low RH.<br>No attribution to anthro. |

# AEROSOL FORCING OF SURFACE IRRADIANCE

## Dependence on aerosol optical thickness

## ***Cloud-free sky***, DOE ARM Site, North Central Oklahoma




*Aerosol scattering **decreases direct irradiance**, **increases diffuse irradiance**.*

*Aerosols **decrease total surface irradiance** (**direct** + **diffuse**) mainly because of upward scattering (top-of-atmosphere forcing) and to lesser extent enhanced atmospheric absorption.*

# APPROACHES TO DETERMINE AEROSOL **DIRECT** RADIATIVE FORCING (*cont'd*)

## 5. *In-situ* Measurements Method

*In-situ* measurement of aerosol optical properties, [chemical, microphysical properties].

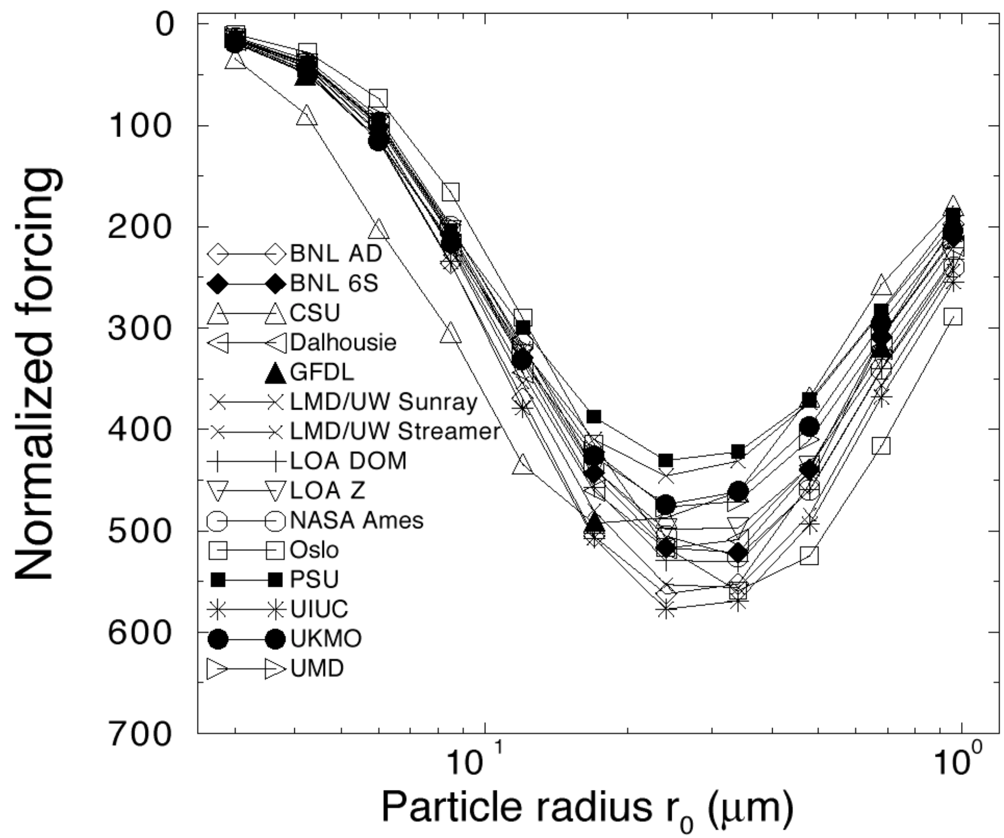
Radiation transfer modeling of forcing.

| STRENGTHS | LIMITATIONS/CONCERNS |
|---|---|
| Accurate forcing estimates | Sparse spatial coverage |
| Account for cloudiness | Sparse temporal coverage |
| [Account for $f$(RH)] | |
| [Attribution to anthro] | |

# INTERCOMPARISON OF BROADBAND SHORTWAVE FORCING BY AMMONIUM SULFATE AEROSOL

Normalized global-average forcing: W m$^{-2}$ / g($SO_4^{2-}$) m$^{-2}$ or W /g($SO_4^{2-}$)

Aerosol optical depth 0.2; surface albedo 0.15




Standard deviation ~8% for 15 models at radius ~ 200 nm.

*Boucher, Schwartz and 28 co-authors, JGR, 1998*

*Radiation transfer models agree closely for well specified aerosol.*

# APPROACHES TO DETERMINE AEROSOL **DIRECT** RADIATIVE FORCING (*cont'd*)

## 6. Chemical Transport Modeling Method

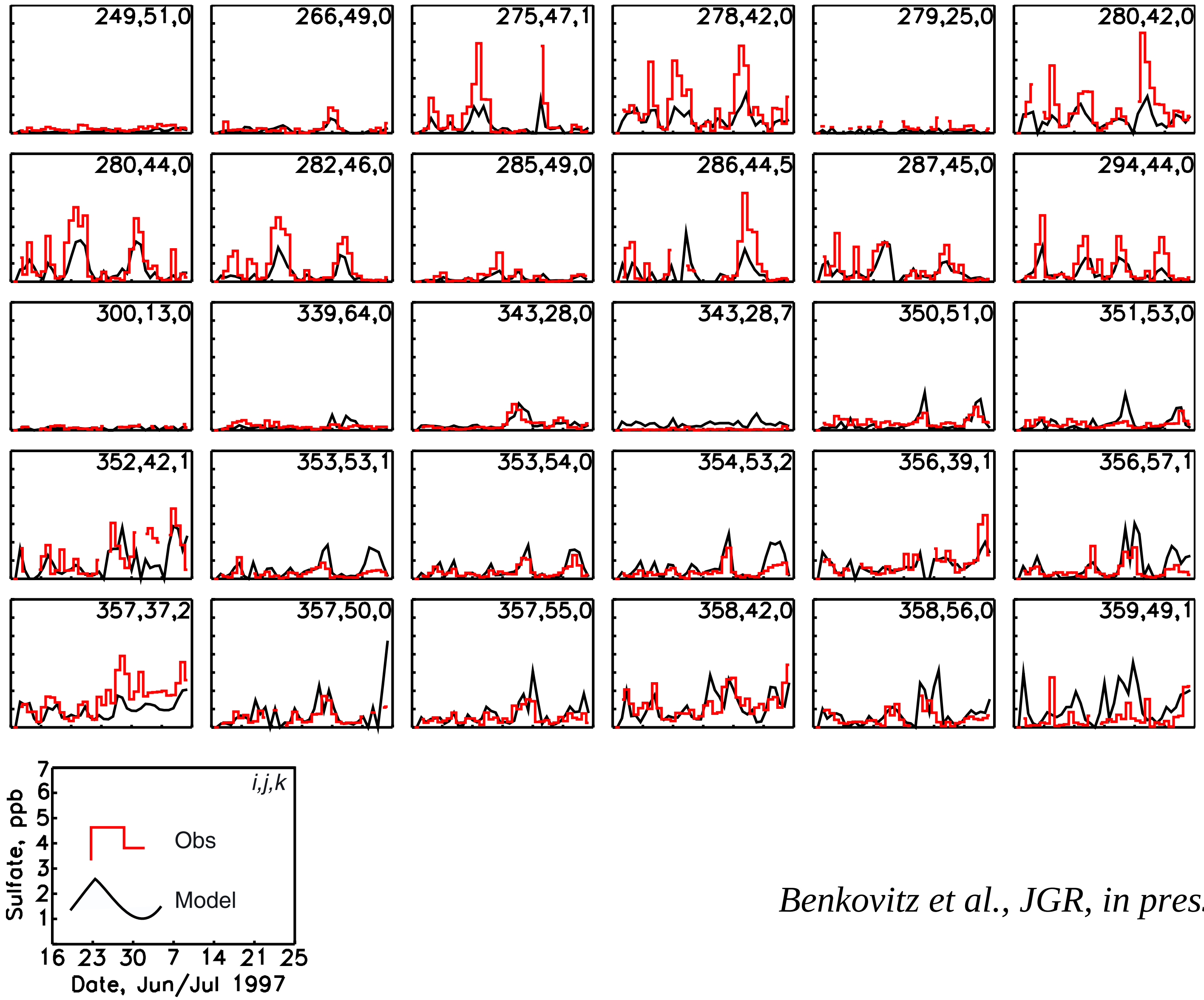
Chemical-microphysical modeling of aerosol loading and properties

Radiation transfer modeling of forcing

| STRENGTHS | LIMITATIONS/CONCERNS |
|---|---|
| Spatial coverage<br>Temporal coverage<br>Account for cloudiness and $f$(RH)<br>Accurate forcing estimates<br>Attribution to anthro | Accuracy of modeled aerosol loading and properties:<br>Sources<br>Transformation<br>Removal<br><u>Need to evaluate model!</u> |

# MODEL-OBSERVATION COMPARISONS

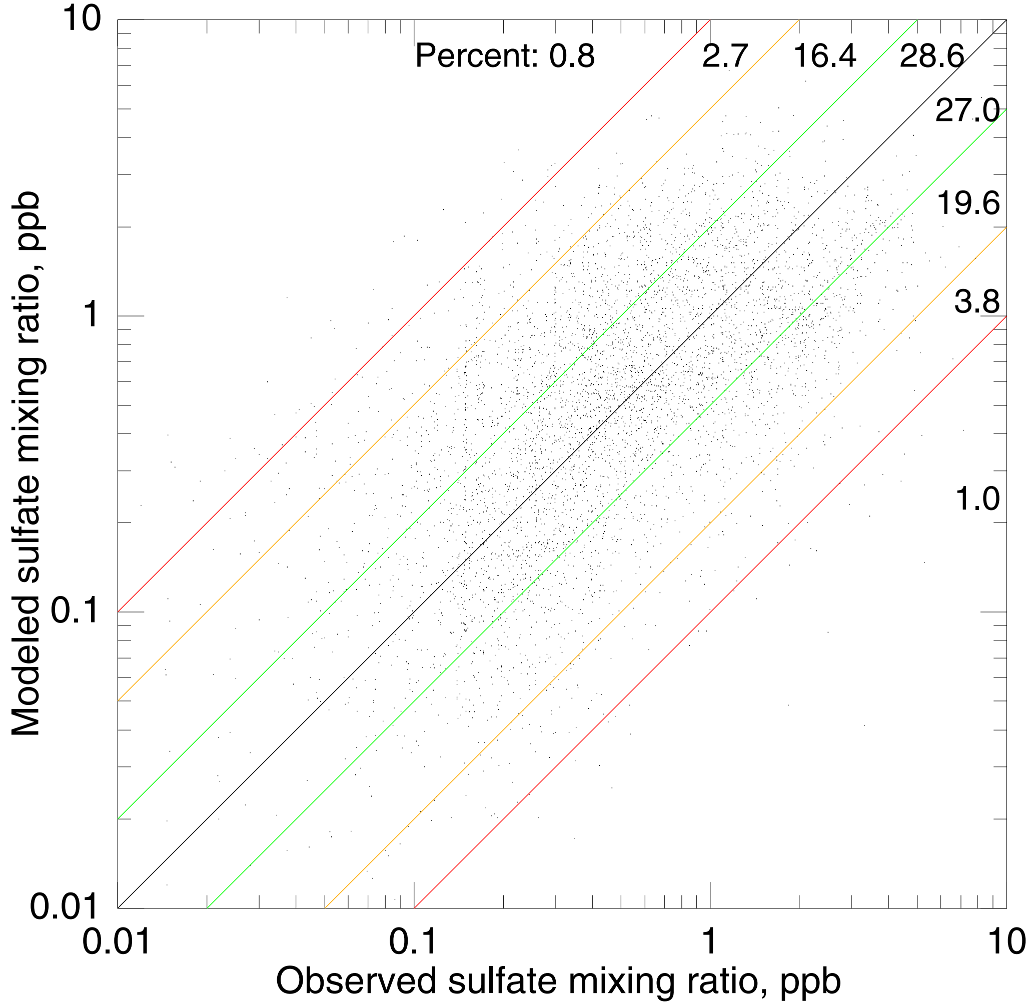
## BNL CTM driven by assimilated meteorological data
## Observed 24-hour sulfate mixing ratio, June-July 1997




*Benkovitz et al., JGR, in press,*

# MODEL-OBSERVATION COMPARISONS

## 5083 24-Hour sulfate mixing ratio in BNL CTM driven by assimilated meteorological data - June-July 1997

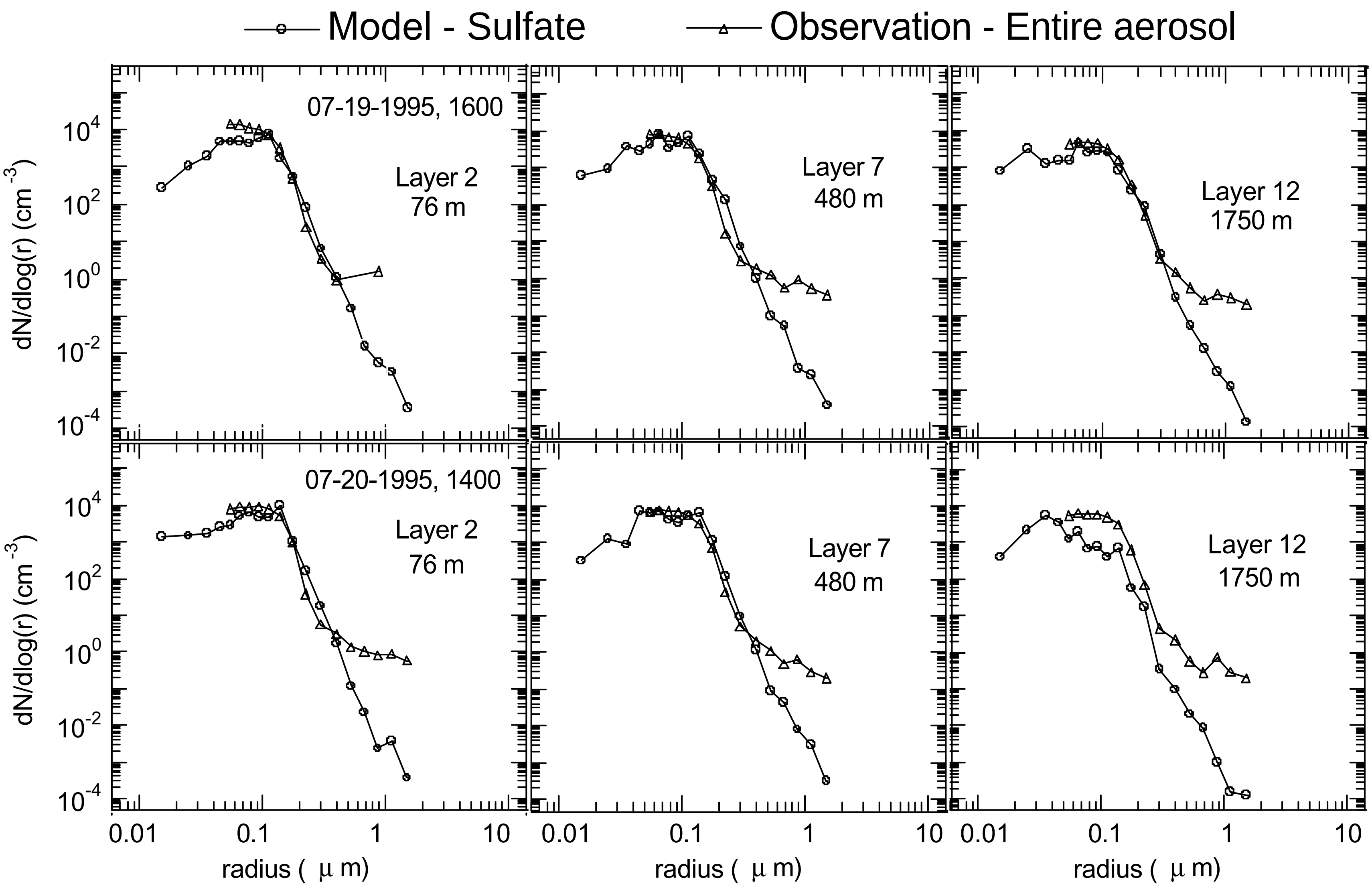



56% of comparisons within factor of 2; 92% within factor of 5.

*Benkovitz et al., JGR, in press, 2004*

# SIZE DISTRIBUTIONS

## Comparison of Measurement and Retrieval from Model
## At 3 Altitudes near Nashville TN

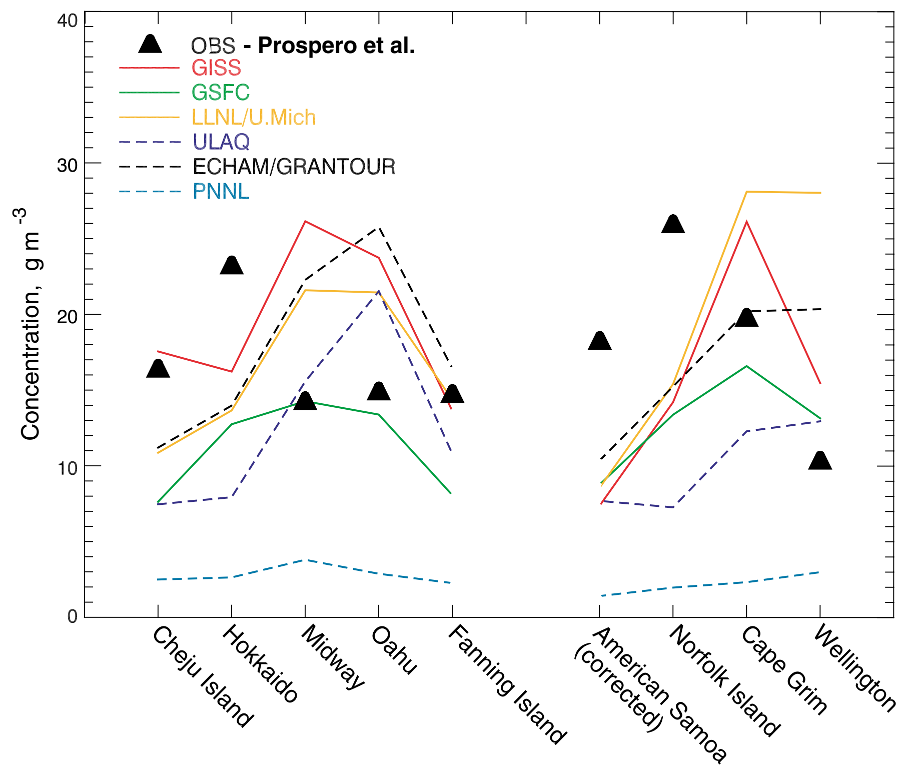


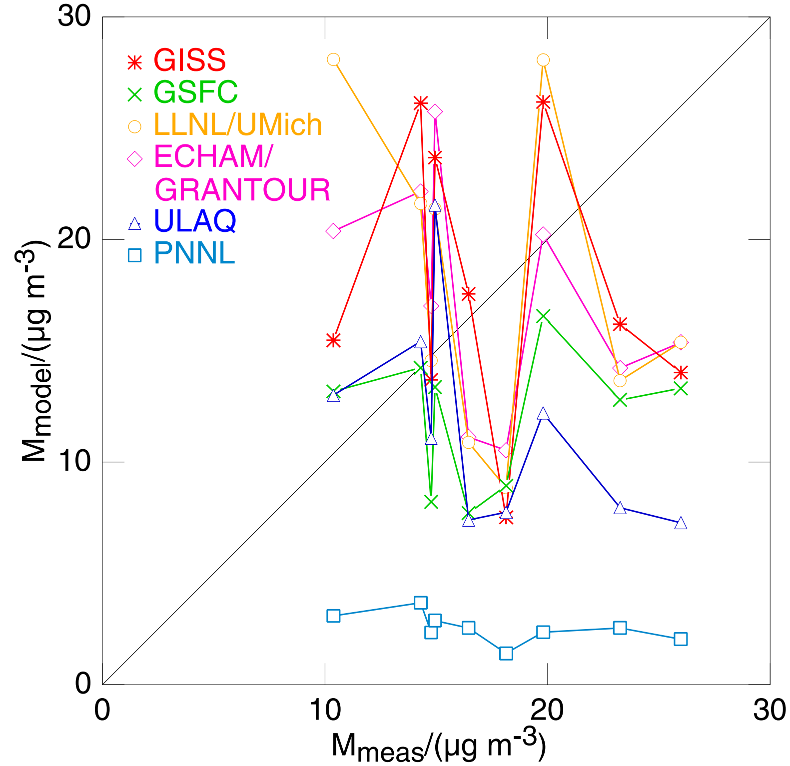

Yu, Kasibhatla, Wright, Schwartz, McGraw & Deng, *JGR*, 2003

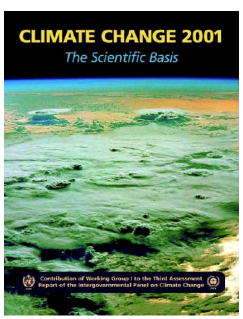
# SEASALT AEROSOL MASS CONCENTRATION

## Modeled and observed annual concentrations

## From IPCC (2001) intercomparison



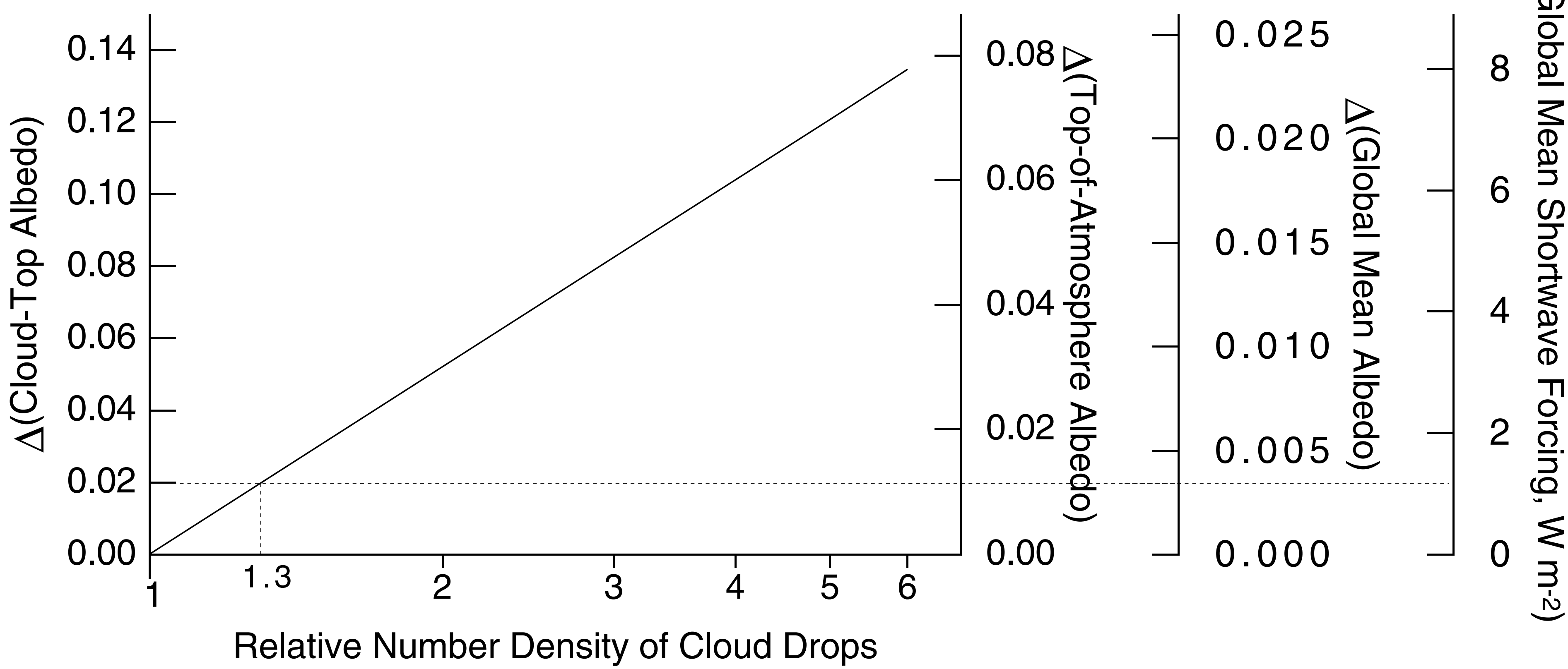




“After throwing out the burdens from models that were outliers in terms of their comparison with observations, the model results for sea salt still differed by a factor of 4.9 and 5.3, for diameter less than and greater than 2 μm, respectively. . . . In the upper troposphere . . . the range increased to as much as a factor of 20 or more.”

# *INDIRECT EFFECT*

## SENSITIVITY OF ALBEDO AND FORCING TO CLOUD DROP CONCENTRATION




*Schwartz and Slingo (1996)*

*Indirect forcing is highly sensitive to small perturbations in cloud drop concentration.*

*A 30% increase in cloud drop concentration results in a forcing of ~1 W $m^{-2}$.*

# CONCLUSIONS AND FUTURE DIRECTIONS

- No silver bullet.
- Radiative measurements must play a key role, but ...
- Chemical transport models, based on understanding of the pertinent chemical and physical processes and extensively evaluated by comparison with observations are essential to interpretation of aerosol radiative influences and attribution to forcing agents.

*THANK YOU*

http://www.ecd.bnl.gov/steve/schwartz.html